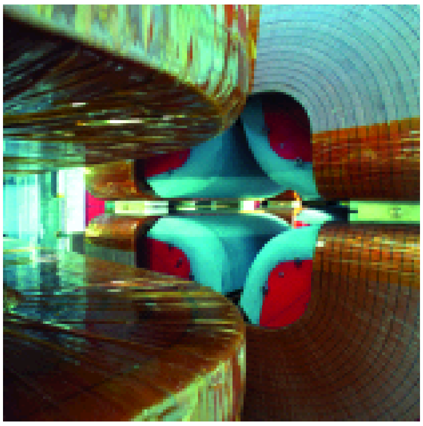
Direct Observation of Bound Beta Decay at the FRS/ESR

In a recent experiment, which combined GSI's fragment separator FRS and the experimental storage ring ESR, bound β decay was directly observed for the first time. The experiment was performed with bare $^{206}Tl^{81+}$ ions stored and cooled in the ESR. Using Schottky mass spectroscopy, the decay of the $^{206}Tl^{81+}$ mother nucleus and the feeding of the bound β daughter $^{206}Pb^{81+}$ could be measured simultaneously.

View into a dipole and quadrupol magnet of the ESR.



The bound β decay mode was predicted in 1947 by the French physicists Jean, Daudel and Lecoin. It took almost 45 years until it was observed in an experiment at the ESR in 1992. In these first measurements, a rather sophisticated but indirect detection scheme was applied [1].

Bound β decay is the time-mirrored process of orbital electron-capture decay. In bound β decay the electron, generated in the decay of the mother-nucleus, is bound in an inner atomic shell (predominantly the 1s-shell) of the daughter atom. An amount of energy equivalent to the atomic binding energy is spared and, therefore, the Q-value is increased compared to the decay into the continuum. Since for neutral atoms—the usual objects of terrestrial β decay studies—a capture of the electron into occupied atomic shells is forbidden by the Pauli principle, bound β decay is an exotic decay mode. It does not occur under normal conditions.

However, when atoms are highly ionized as, e.g., during the stellar nucleosynthesis, bound β decay can become a very significant decay branch. Then β lifetimes may change by many orders of magnitude with respect to those of the corresponding neutral atoms, as has been shown for several cases in experiments at the ESR.

For the present experiment, bare $^{206}Tl^{81+}$ was chosen as the mother atom. It transforms by bound β decay into hydrogen-like $^{206}Pb^{81+}$ with a branching ratio of 10 - 20 % [2]. The Q-value, i.e. the mass difference between mother and daughter, is about 1.6 MeV.

The radioactive $^{206}Tl^{81+}$ ions were produced by fragmentation of a 250 AGeV ^{208}Pb beam and separated from other reaction products using GSI's fragment separator. The isotopically (almost) pure $^{206}Tl^{81+}$ beam was then injected into the ESR and cooled to a low momentum width.

While circulating in the ESR the bare $^{206}Tl^{81+}$ ions decay into the bound β daughter $^{206}Pb^{81+}$. Due to electron cooling both ion species travel at the same velocity but—as a consequence of their mass difference—on slightly different orbits and with slightly different revolution frequencies. The lower frequency corresponds to the heavier $^{206}Tl^{81+}$ mother and the higher frequency to the lighter $^{206}Pb^{81+}$ daughter.

Employing the technique of Schottky mass spectroscopy, these different revo-

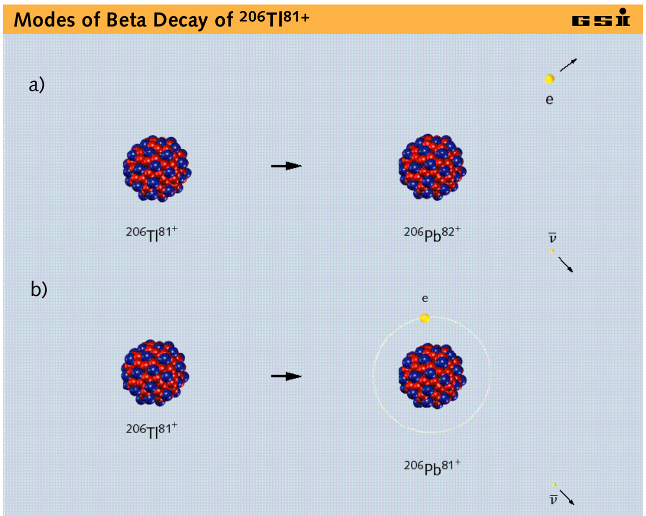


Figure 1: *While in usual β decay the electron goes into a continuum state (a), it is captured and bound in an inner atomic shell in bound β decay (b).*

lution frequencies—differing by a factor of only 10^{-6}—could be resolved. Figure 2 shows such a Schottky frequency spectrum which was recorded about 8 minutes after injection of the $^{206}Tl^{81+}$ beam. Three ion species are well-resolved: bare $^{206m}Tl^{81+}$ ions in an isomeric, long-lived state (green); bare $^{206}Tl^{81+}$ ions in their ground state (blue), and their bound β decay daughters, hydrogen-like $^{206}Pb^{81+}$ ions (red).

Recording the evolution of the Schottky peaks as a function of time, this technique allows to observe the decreasing $^{206}Tl^{81+}$ intensity and the increasing $^{206}Pb^{81+}$ intensity simultaneously. This is illustrated in Figure 3 which shows the height of the Schottky signals measured for the three ion species as function of time after injection. Time intervals in the laboratory are different by a factor $\gamma \approx 1.25$ from intervals of proper time of the circulating ions due to the relativistic time dilatation. The colors in the figure represent the respective signal heights, going from red (high) via yellow and green to blue (low). While the two Schottky peaks belonging to $^{206}Tl^{81+}$ in its ground and isomeric state, respectively, decrease as a function of time, the $^{206}Pb^{81+}$ signal shows a smooth increase and then slowly decreases again due to beam losses caused by charge changing processes with rest gas atoms and electrons in the cooler. From the signal increase observed for $^{206}Pb^{81+}$ the branching ratio for bound β decay can be estimated.

In summary bound β decay could be directly observed for the first time employing Schottky mass spectroscopy at the ESR. The experiment demonstrates the potential of the Schottky technique for β decay studies in general: total and partial β lifetimes can be measured, and the mass difference between mother and daughter atoms can be determined with high precision. By measuring the branching ratio of the bound β decay for a given system, one also gets information on the Fermi function in β^- decay of atomic nuclei, which so far was not accessible to experimental investigations. ■

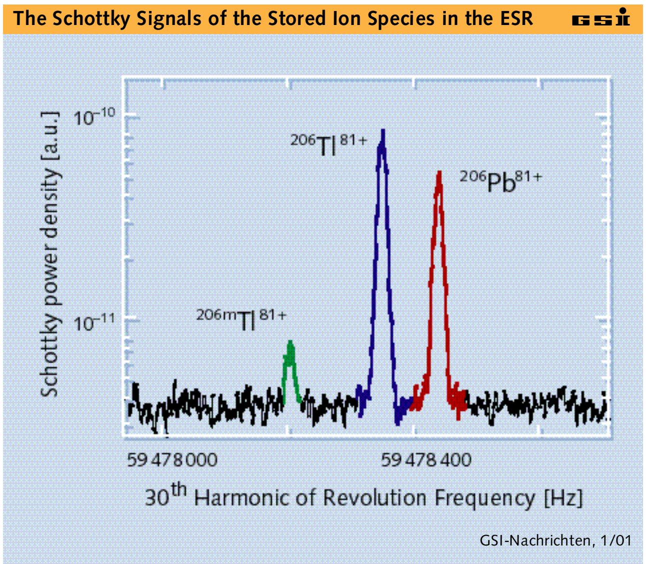


Figure 2: *Schottky frequency spectrum of $^{206}Tl^{81+}$ and $^{206}Pb^{81+}$ recorded by the 30th harmonic of the revolution frequency. The picture shows the well-resolved Schottky signals of the bare $^{206}Tl^{81+}$ ions in an isomeric nuclear state ($^{206m}Tl^{81+}$, green), bare $^{206}Tl^{81+}$ ions in the nuclear ground state ($^{206}Tl^{81+}$, blue), and their hydrogen-like bound β decay daughters $^{206}Pb^{81+}$ (red).*

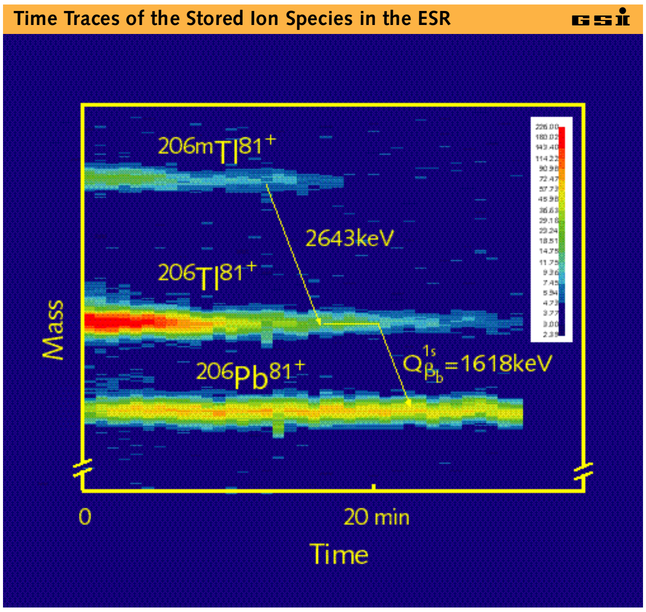


Figure 3: *Time dependence of the intensities of the three Schottky peaks for $^{206m}Tl^{81+}$, $^{206}Tl^{81+}$ and their bound β decay daughter $^{206}Pb^{81+}$, respectively. The signals were observed for about 25 minutes after injection into the ESR. The injection pulse contained about 1000 $^{206}Tl^{81+}$ ions. The vertical axis shows the frequency scale of Fig. 2, converted to a mass scale. Also indicated are the corresponding mass differences (Q-values).*

REFERENCES

[1] F. Bosch et al., Phys. Rev Lett. 77, 5190 (1996)
[2] F. Bosch et al., GSI Annual Report 2000